NASA/TM-2001-210393

Comparison of X-31 Flight and Ground-Based Yawing Moment Asymmetries at High Angles of Attack

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May 2001

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May 2001

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ABSTRACT

Significant yawing moment asymmetries were encountered during the high-angle-of-attack envelope expansion of the two X-31 aircraft. These asymmetries caused position saturations of the thrust-vectoring vanes and trailing-edge flaps during some stability-axis rolling maneuvers at high angles of attack. The two test aircraft had different asymmetry characteristics, and ship 2 has asymmetries that vary as a function of Reynolds number. Several aerodynamic modifications have been made to the X-31 forebody with the goal of minimizing the asymmetry. These modifications include adding transition strips on the forebody and noseboom, using two different length strakes, and increasing nose bluntness. Ultimately, a combination of forebody strakes, nose blunting, and noseboom transition strips reduced the yawing moment asymmetry enough to fully expand the high-angle-of-attack envelope. Analysis of the X-31 flight data is reviewed and compared to wind-tunnel and water-tunnel measurements. Several lessons learned are outlined regarding high-angle-of-attack configuration design and ground testing.

NOMENCLATURE

C_d	cylinder drag coefficient
C_n	yawing moment coefficient
C_{n_0}	yawing moment coefficient at 0° angle of sideslip
C_Y	side force coefficient
$\lvert C_Y \rvert_{max}$	maximum absolute value of the side force coefficient
d	noseboom diameter
D	forebody or ogive base diameter
g	acceleration caused by gravity
l	body length
Re_D	Reynolds number based on a forebody base diameter of 3.2 ft (97.5 cm)
Re_d	Reynolds number based on a noseboom diameter of 3.5 in. (8.9 cm)
S1	strake 20-in. (50.8-cm) long by 0.60-in. (1.52-cm) wide
S2	strake 47-in. (119.4-cm) long by 0.60-in. (1.52-cm) wide
V	velocity
α	angle of attack, deg

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INTRODUCTION

Two X-31 aircraft (fig. 1) were designed and built to support the Enhanced Fighter Maneuverability (EFM) research program,[1] which was jointly funded by the United States Defense Advanced Research Projects Agency (DARPA) and the German Federal Ministry of Defense. The flight test portion of the program was conducted by an international test organization composed of the National Aeronautics and Space Administration (NASA), the U. S. Navy, the U. S. Air Force, Rockwell International (Downey, California), and Deutsche Aerospace (DASA). The goals of the flight program were to demonstrate enhanced fighter maneuverability technologies, investigate close-in–combat exchange ratios, develop design requirements, build a database for application to future fighter aircraft, and develop and validate low-cost prototype concepts.

During the 1-*g*, high-angle-of-attack envelope expansion, both X-31 test aircraft exhibited significant, but different, yawing moment asymmetries at 0° angle of sideslip at angles of attack greater than 40°. Resulting aircraft responses included slow rolloffs and "lurches" (small, sharp, heading changes). Although pilot compensation was attainable, as much as 50 percent of roll-stick deflection was required to counter the asymmetry. Consequently, the full-stick velocity vector roll rate of each aircraft was found to be faster in the direction of the asymmetry at a constant angle of attack. To coordinate maneuvering with the yawing moment asymmetries, the control system had to increase the amount of control deflection required. In many cases, this increase resulted in a position saturation of one of the trailing-edge flaps or thrust-vectoring paddles.

In an attempt to reduce the yawing moment asymmetry, transition grit strips were applied along the forebody to force boundary-layer transition at the same location on both sides of the forebody. This method had shown some promise in reducing high-angle-of-attack yawing asymmetries during earlier tests on the F-18 High Alpha Research Vehicle (HARV).[2] Transition strips were also installed along the noseboom with the hopes that a turbulent separation from the cylindrical cross section would result in a reduced wake impinging on the forebody. These configuration changes somewhat improved the pilot-reported handling qualities; however, the asymmetries were not eliminated.

Shortly into the high-angle-of-attack, elevated-*g* phase of the envelope expansion, a departure from controlled flight occurred on ship 2 as the pilot was performing a 2-*g*, split-S maneuver to 60° angle of attack. Data analysis showed that a large, unmodeled yawing moment, in excess of the available control power, had triggered the departure. The forebody vortex system was suspected to be the moment generator.

An effort was begun to design and test forebody strakes that would improve the forebody vortex symmetry and eliminate any large-amplitude asymmetry changes like those seen during the departure. Towards this goal, a wind-tunnel test[3] was conducted in the NASA Langley Research Center (Hampton, Virginia) 30- by 60-Foot Wind Tunnel to define the strake design and document any changes to the static stability characteristics. The test resulted in the installation and flight test of small forebody strakes that ultimately reduced the asymmetry enough to fully achieve all of the flight test objectives. Shortly after the strake design, a water-tunnel test[4] was conducted in the NASA Dryden Flight Research Center (Edwards, California) Flow Visualization Facility to investigate the variation in forebody flow characteristics as a function of configuration changes.

This report summarizes the effectiveness of the configuration modifications that were flight-tested and the usefulness of the ground test facilities at predicting the X-31 forebody aerodynamics. The lessons learned during the X-31 program illustrate the sensitivity of forebody aerodynamics to Reynolds number and seemingly minor configuration changes.

FOREBODY AERODYNAMICS BACKGROUND

The long, slender, forebody shapes of modern fighter aircraft make them susceptible to the forebody side force phenomenon. This side force is the result of surface pressure imbalances around the forebody caused by an asymmetric forebody boundary-layer separation and vortex system at high angles of attack. In this scenario, the boundary layer on each side of the forebody separates at different locations as shown in the forebody cross section in figure 2. At separation, corresponding vortex sheets are generated that roll into an asymmetrically positioned vortex pair. The forces on the forebody are primarily generated by the attached flow and to a lesser extent by the vortices, depending on their proximity to the forebody surface. Figure 2 shows a typical asymmetrical arrangement in which the lower, more inboard vortex corresponds to a boundary layer that separated later and the higher, more outboard vortex corresponds to the boundary layer that separated earlier. The suction generated by the longer run of attached flow and the closer vortex combine to create a net force in that direction. Because the aircraft center of gravity is well aft of the forebody, a sizable yawing moment asymmetry develops.

The asymmetry problem was illustrated by measuring the side force on an axisymmetric body at different roll angles and angles of attack. Because the model is axisymmetric, no lateral-directional forces or moments would be expected. Figure 3, however, shows that a large asymmetry develops on a 3.5-*l/D* fineness-ratio ogive model at approximately 35° and continues to greater than 70° angle of attack.[5] In addition, as the ogive is rotated around its axis of symmetry, the sign of the asymmetry changes at a roll angle of 270°. Further tests by other researchers confirmed that the magnitude of the asymmetry does not change smoothly with changing roll angle[6–8] (fig. 4). Instead, as the ogive cylinder is rolled through 360°, four changes in the sign of the asymmetry occur. Thus, at high angles of attack, the vortex cores can have bistable states, neither of which is symmetric. Other tests have shown that rotation of the nosetip alone produces the same result, suggesting that microasymmetries near the model tip are significant in the asymmetry formation.[5, 7, 9–11]

Reynolds number also has been shown to affect the asymmetry characteristic of slender bodies.[5, 6, 9, 12] Figure 5 shows that large changes in the magnitude and sign of the asymmetry can be affected by Reynolds number; however, the angle-of-attack range over which the aircraft is susceptible to asymmetries remains unchanged. The nature of the boundary-layer separation on the forebody—whether it is laminar, transitional, or fully turbulent—depends on the Reynolds number. At angles of attack greater than 30°, the maximum side force on a 3.5-*l/D* ogive is significantly larger for laminar and turbulent separation conditions than it is with transitional flow (fig. 6). This Reynolds number effect is important when comparing flight-derived asymmetry information with either wind-tunnel or water-tunnel data.

Several methods have been used to reduce the asymmetry characteristics of high-angle-of-attack aircraft. The traditional passive method of controlling the forebody vortex location has been to use longitudinal strakes near the apex on both sides of the forebody. Techniques that address the boundary-layer state have also gained attention. Because the nosetip appears to have a large influence on the asymmetry, several modifications to it also have been studied.[5, 7, 9–11]

Strakes have been shown to reduce or eliminate high-angle-of-attack side force asymmetries on generic cone and ogive shapes[9, 13] and realistic aircraft forebodies.[14–17] Cases of strakes not fully eliminating the asymmetry have also been found.[18] The addition of strakes near the nosetip produces several beneficial effects on the forebody flow field. First, the strakes tend to mask the presence of microasymmetries on the model or aircraft. Second, the strakes fix the boundary-layer separation line on the body, eliminating asymmetric boundary-layer separation as a cause of vortex asymmetry. Last, the strakes increase the vorticity (and thus the strength) of the primary vortex cores, making them less susceptible to other flow fields such as the canard or wing.

Boundary-layer transition, or “trip,” strips also have had limited success at reducing asymmetries. One use of transition strips is to ensure the boundary layer transitions to a turbulent state symmetrically on both sides of the forebody. Having similar boundary-layer states should promote symmetrical separation and vortex formation. In limited tests on the HARV,[2] a symmetrically applied transition grit strip eliminated the asymmetric separation caused by asymmetric vortices. Excellent reviews of the high-angle-of-attack vortex asymmetry problem have been compiled by Hunt[19] and Ericsson.[20]

FLIGHT TEST RESULTS

Flight data were recorded during the high-angle-of-attack envelope expansion of the two X-31 aircraft. Additional analysis of the X-31 yawing moment asymmetry flight data is discussed in references 21 and 22.

Method

To better understand and quantify the high-angle-of-attack yawing moment asymmetry characteristic of the X-31 aircraft, a method has been developed to calculate time histories of the asymmetric forces and moments on the aircraft from flight data. Figure 7 shows a block diagram of the method. The flight-measured yawing moment is computed by substituting the measured variables into the rigid-body equation of motion. The yawing moment predicted from the simulation aerodynamic and thrust databases is then subtracted from the flight-measured moment to calculate the missing, unmodeled components.

By restricting data analysis to symmetrical maneuvers in which sideslip, roll rate, and yaw rate are small, the cause of the missing aerodynamic yawing moment has been narrowed to three main sources: errors in the thrust-vectoring model; errors in the control effectiveness model; and aerodynamic asymmetries. Because the control effectiveness database was verified and updated with parameter identification results and the thrust model errors were not expected to be a strong function of angle of attack, any changes in the missing components with increases in angle of attack were attributed to aerodynamic asymmetries. An analysis of multiple decelerations, pullups, and split-S maneuvers with the same aircraft configuration resulted in a composite of the asymmetry characteristic for the given configuration at a given flight condition.

Maneuver Technique

The X-31 control laws were designed to allow the pilot to command angle of attack with the pitch stick, stability-axis roll rate with the roll stick, and angle of sideslip with the rudder pedals. The angle-of-sideslip commands were faded to 0° between 30° and 50° angle of attack. Two control-law features made the maneuvers shown herein nearly independent of pilot technique. One of these features was an angle-of-attack limiter. The angle-of-attack limiter allowed the pilot to set the maximum angle-of-attack command that the control laws would generate for a specific maneuver, which permitted the pilot to pull the stick aft of the target command, resulting in an angle-of-attack command that stopped at the limiter setting. The other feature was a 25-deg/sec rate limiter on the angle-of-attack command. Thus, when the pilot pulled the stick quickly aft to the stop, the angle-of-attack command would ramp in to the preselected angle-of-attack limit and remain constant until the pilot released the stick. This technique resulted in nearly identical control system commands for each of the dynamic maneuvers.

Flight Test Configurations

The X-31 forebody is elliptical in cross section with an *l/D* ratio of approximately 2.2. The aircraft was always flown with an underslung noseboom (fig. 8). The bluntness of the nosetip (nosetip radius divided by forebody base radius) was 0.003 in its unmodified configuration. During the course of the study, the following configuration changes were tested (fig. 8):

- S1, a strake 20-in. (50.8-cm) long by 0.60-in. (1.52-cm) wide with nosetip blunting
- S2, a strake 47-in. (119.4-cm) long by 0.60-in. (1.52-cm) wide with nosetip blunting
- Forebody transition strip
- Noseboom transition strip

Whenever the vehicles were flown with a strake, the radius of the nosetip was increased. On ship 1, the nosetip radius was increased to 0.75 in. (0.039 nosetip bluntness). On ship 2, the radius was increased to 0.50 in. (0.026 nosetip bluntness). The transition strips consisted of number 30 Carborundum™ (Saint Gobain Industrial Ceramics; Amherst, Massachusetts) grit. Because the objective was to rapidly alleviate the asymmetry problem, these configuration modifications were not systematically evaluated. The sequence of test configurations was as follows:

Ship 1	**Ship 2**
Unmodified forebody	Unmodified forebody
Forebody and noseboom transition strips	Forebody and noseboom transition strips
S1 and noseboom transition strip	Forebody transition strip
S1 and forebody and noseboom transition strips	S1 and noseboom transition strip
S1 and noseboom transition strip	S2 and noseboom transition strip

Ship 1 Asymmetries

Figure 9 shows the yawing moment asymmetry for the X-31 ship 1 during slow (approximately 1-*g*) decelerations to high-angle-of-attack conditions for several of the flight configurations. The largest asymmetry began building up at 48° angle of attack and had a peak yawing moment asymmetry of $C_{n_0} = -0.063$ at approximately 57° angle of attack. The asymmetry diminished significantly in magnitude by 65° angle of attack.

To mitigate these asymmetries, a transition grit strip was installed on both sides of the forebody and along the sides of the noseboom. Unfortunately, the data (fig. 9) indicate that the asymmetry problem was magnified. Although the largest asymmetry began to build at the same angle of attack (48°), the peak asymmetry increased to $C_{n_0} = -0.078$. The addition of the transition strips increased the angle of attack at which the largest asymmetry occurred from 57° to 61°.

The replacement of the forebody transition strip with the S1 strake, combined with the blunting of the nosetip, effectively delayed the initiation of the yawing moment asymmetry to a maximum of 55° angle of attack. A peak asymmetry of $C_{n_0} = -0.040$ occurred at 60° angle of attack, after which the asymmetry diminished. As with the unmodified forebody, the aircraft became nearly symmetric by 65° angle of attack.

The addition of a boundary-layer transition strip along the forebody aft of the strake resulted in an increase in the asymmetry level. A sharp change in the asymmetry occurred at approximately 55° angle of attack. An asymmetry level of $C_{n_0} = -0.050$ remained over an angle-of-attack range from 59° to 66°. Thus, the addition of the forebody transition strip increased the yawing moment asymmetry and caused it to remain at its largest level for a broader angle-of-attack range.

Ship 2 Asymmetries

The yawing moment asymmetry characteristic of ship 2 was significantly more troublesome than that of ship 1; thus, greater effort was made to reduce the asymmetry on ship 2 through configuration changes. In addition to the configuration changes flown with ship 1, the extended-length strake, S2, was also tested.

Unlike ship 1, a comparison of multiple 1-*g* maneuvers using the unmodified forebody did not show a repeatable trend in the asymmetry as angle of attack increased. Each maneuver appeared to have a random asymmetry pattern. Plots of the asymmetry range as a function of angle of attack (fig. 10) show that the maximum yawing moment asymmetry appears to be bounded at $|C_{n_0}| < 0.10$.

The addition of forebody and noseboom transition strips resulted in a more repeatable asymmetry characteristic than that for the unmodified forebody during 1-*g* decelerations; however, some scatter still existed about the average asymmetry. Figure 11 shows the range of the scatter for this configuration. The asymmetry initially went to the right to a peak of a maximum of $C_{n_0} = 0.050$ at an angle of attack between 48° and 54°. As the angle of attack increased, the asymmetry switched to the left, eventually reaching its maximum asymmetry at approximately 67° angle of attack. The switching of the asymmetry from the right to left resulted in a change in the yawing moment of between 0.10 and 0.14.

Figure 11 also shows that two different asymmetry characteristics developed on ship 2 when the noseboom transition strip was removed, leaving the forebody transition strip in place. Calculating the approximate crossflow Reynolds number based on noseboom diameter for each of the maneuvers shows that the two asymmetry characteristics occurred over distinct Reynolds number ranges. Plotting both Reynolds number ranges on a chart of the boundary-layer separation state of a circular cylinder as a function of Reynolds number (fig. 12) shows that a difference in the boundary-layer state at separation could have existed between the two sets of data. The lower Reynolds number data, which would result in a large separation wake, had a sharp change in the asymmetry at angles of attack greater than 50° that built up to a large right asymmetry. Conversely, the higher Reynolds number flow, which would produce a smaller separation wake, had a milder buildup in asymmetry. The higher Reynolds number data more closely matched the data with the noseboom transition strips installed, suggesting that the strip was successful in eliminating a laminar separation, as it was originally intended to do.

The first real improvement in the yawing moment asymmetries on ship 2 was found with the addition of forebody strakes and the blunting of the nosetip. Figure 13 shows data from the S1 and S2 strake flight tests. The combination of the S1 strake, 0.5-in.-radius blunt nosetip, and noseboom transition strip resulted in a comparably slow buildup of asymmetry starting at approximately 50° angle of attack. The asymmetry reached a peak value of C_{n_0} = –0.059 at 60° angle of attack. As with most other configurations, the asymmetry diminished to nearly zero by 70° angle of attack. The addition of a transition strip aft of the S1 strake increased the maximum asymmetry from C_{n_0} = –0.059 to C_{n_0} = –0.078. This increase was similar to that seen on ship 1. Because the 20-in.-long S1 strake reduced the maximum yawing moment asymmetry level, a longer 46-in. strake, S2, was installed and flight-tested with the blunt nosetip. Unfortunately, little change in the 1-*g* deceleration asymmetries resulted. The longer strake did shift the asymmetry to a higher angle of attack by approximately 2°.

Dynamic High-Angle-of-Attack Maneuvers

Figure 14 shows the asymmetries calculated during rapid pullups to high angles of attack for ship 1 for the configuration that had the S1 strake, blunted nose, and noseboom transition strip. The data obtained from the 1-*g*, quasi-steady-state decelerations are plotted with the dynamic data for comparison. The asymmetry level during the dynamic maneuvers generally was less than or equal to the value seen in the 1-*g* maneuvers at the maximum asymmetry angle of attack (approximately 60°). This reduction in asymmetry level during the dynamic portion of the maneuver, however, was not entirely useful. As the aircraft reached its target angle of attack and the load factor decayed to unity, the asymmetry often built up to the steady-state value. Thus, the maximum asymmetry defined by the 1-*g* decelerations provided the "worst-case" levels for which the flight control system had to account. Although the dynamic maneuvers reduced the maximum asymmetry at approximately 60° angle of attack, an increase in the asymmetry was seen at lower angles of attack (approximately 45°–50°).

Similar results were found for ship 2, except that the maximum asymmetry measured when capturing 50° angle of attack increased with increasing Reynolds number (fig. 15). Although the addition of the S2 strake did not appear to reduce the maximum asymmetry at 60° angle of attack, the tendency of the asymmetry to go right at 50° angle of attack during dynamic maneuvers appeared to be significantly reduced.

COMPARISON TO WIND-TUNNEL RESULTS

Shortly after the yawing moment–induced, high-angle-of-attack departure of the X-31 ship 2, a wind-tunnel test[3] was conducted in the NASA Langley 30- by 60-Foot Wind Tunnel. The goal of the wind-tunnel test was to aid design of a simple forebody modification that would reduce the high-angle-of-attack yawing moment asymmetry to allow completion of the high-angle-of-attack envelope expansion.

Although some yawing moment asymmetry was predicted in the wind tunnel at the high-angle-of-attack condition, the magnitude was significantly less than that seen in flight (fig. 16). One possible explanation has to do with Reynolds number. A plot of the asymmetry as a function of Reynolds number for an ogive (fig. 6) shows a significant decrease in the asymmetry at Reynolds numbers that result in mixed boundary-layer states on the forebody. The boundary layers that are dominated by laminar or turbulent flow result in similar, large-amplitude asymmetries. If this phenomenon holds true for realistic forebodies in flight, then the Reynolds number of the 30- by 60-Foot Wind Tunnel test could have been responsible for the failure to predict the large amplitude asymmetry. Both the water-tunnel and the flight test Reynolds numbers appear to be well outside of this Reynolds number range.

The wind-tunnel test showed that strakes running longitudinally along the waterline of the forebody from the nosetip reduced the model yawing moment asymmetry. The effectiveness of the strakes at reducing the asymmetry was not a function of the strake width. As previously shown, two different length strake sets were flight-tested and evaluated. Two strake designs, 20-in. (50.8-cm) and 47-in. (119.4-cm) long, were manufactured and flight-tested in separate tests. Both strakes were 0.60-in. (1.52-cm) wide.

The wind-tunnel test was also used to predict the changes to the basic aircraft static aerodynamics caused by the strakes. These predictions were important because several of the candidate strake designs caused undesirable changes to the yawing moment caused by angle of sideslip or the static pitching moment. As an

CHAPTER 1

The Problem

On ditching in warm or cold water the inability to breath-hold long enough to make an escape from the rapidly sinking, flooded, inverted helicopter represents a major hazard. This hazard increases in cold water because, in this situation, maximum breath-hold time can be just a few seconds.

In the US Navy Journal, "*All Hands*," (45), McKinley reported vividly the life-threatening situation following a ditching experienced by a US Navy helicopter crew. This is quoted in full below:

"The impact was tremendous. The helo lost power and dropped 500 feet in five seconds. The disabled Navy HH-46 Sea Knight Helicopter slammed into the Indian Ocean so that one survivor, Aviation Ordinanceman 3rd Class Francis Garcia, is not certain to this day, whether the troop seat he was sitting on just collapsed or whether he was actually driven through the webbing of the seat by the impact. In either case, he was sprawled painfully on the helo's hard deck as seawater began to flood in.

Aviation Machinist's Mate 1st Class Timothy Chayka, the crew chief of the HH-46 was also blanketed by the torrent of water gushing through the ruptured fuselage.

The force of the crash had snapped the cockpit off from the rest of the aircraft. The pilot, Lt. Steven Rosandich, smashed against the door and broke his jaw. Co-pilot Lt. Gregory LaFare, watched helplessly as the windshield collapsed in on him and Rosandich. The instrument panel crushed against their legs and pinned them in the ruined cockpit. Both flyers were immediately swallowed by the water and behind them; Chayka and Garcia were also sinking in the wreckage. Four men - hurt, stunned, and disoriented, were desperately struggling to save themselves as their shattered aircraft sank between the waves of the Indian Ocean."

The problem is not unique to the naval aviator; it can threaten any military or civilian helicopter pilot, crew, and passengers that fly over water, and for that matter any fixed wing aircraft pilot and crew that may be unfortunate to ditch or crashland in water. Nor is it an uncommon or trivial problem.

1.1 The Extent of the Problem: World-wide Military and Civilian Helicopter Ditching Statistics

Helicopter ditchings are not uncommon. The United States Navy, being the largest operator of military helicopters over water, has published the most extensive data relating to ditchings: the first were reported by Cunningham in 1978, (26). Statistics from the Naval Safety Centre show that from July 1963 to February 1975, 234 helicopters, with a total of 1,093 occupants crashed or ditched at sea. 196 persons died in these accidents, 130 were listed as lost/unknown, and 29 suffered either a fatal injury or an injury which caused drowning. The remaining 37 victims were not injured, but drowned nonetheless. Of the 897 survivors, 437 (49%) egressed underwater. The success rate for aviators trained for underwater egress was 91.5%. The success rate for those who had not been trained was 66%.

In 1992, the United States Navy updated these statistics with a series covering 1977 to 1990. During this period there were 137 accidents and a survival rate of 83% (6). These figures were again updated in 1996: from 1977 - 1995 there was an overall survival rate of 75% associated with survivable Class A over-water mishaps (7). The survival rate associated with night accidents for the AH-1, CH-46, and CH-53 were lower; and for the CH-46, less than 50% of the victims survived. In 1998 data covering 1985 to 1997 were reported (40, 41). The survival rate in the 44 daylight ditchings was 88%; this compared with a rate of 53% in the 23 ditchings that occurred at night. These data confirm the intuitive belief that, from the point of view of survivability, flying over water in a helicopter at night is even more dangerous than during the day.

From 1958 to 1988, the Canadian military (13) had at least seven helicopter accidents in fresh water (data from the late fifties to mid-sixties are sparse and incomplete). Nineteen personnel were involved, of which ten died in three accidents, a survival rate of 47%. From 1967 to 1997, the Canadian Military (12) had 14 helicopter accidents in seawater, 62 personnel were involved, of which six died in three accidents; a survival rate of 90%.

Giry (32) has analysed the French military helicopter accident data. Between 1980 and 1991, 11 helicopters ditched; the survival rate was 65%.

In 1988, Baker and Harrington analysed the RN helicopter ditchings between 1974-1983 (4), they noted that 15 of 43 survivors (35%) reported major difficulties escaping, caused by in-rushing water disorientation; confusion; panic; entanglement with debris; and unfamiliarity with exiting release mechanisms. In the same year, Vyrnwy-Jones and Turner (74) reported that in 47% of RN helicopter accidents between 1972-1984 the helicopter sank or immediately inverted on arriving at the water. Reader (49) reported the British Military army, navy, and air force helicopter accidents between 1972 to 1988. During this period there were 94 accidents involving 342 occupants. There were 58 fatalities and 41 injuries; the survival rate was 83%.

In contrast to the statistics presented above that show a survival rate of 55 - 85% in a survivable accident, the German military reported only one helicopter ditching between 1984 and 1997. In this Sea King accident there were no fatalities (44).

In 1992, Steele Perkins (56) did a brief review of seventeen Royal Navy ditchings between 1982 and 1991. One of the principal conclusions was that the addition of a Short Term Air Supply System for the crew would improve survivability.

On the civilian side, in 1984, Anton (3) reported that of seven survivable accidents in the North Sea between 1970-1983, in three cases the aircraft capsized either immediately on ditching or very shortly afterwards. The susceptibility of an aircraft to inversion after ditching (stability) is closely related to sea state. Of the ditchings examined by Anton, the four that ditched in sea state 4 and higher all capsized. To comply with airworthiness requirements a helicopter has to demonstrate stability in up to sea state 6. In the North Sea, the sea state falls below sea state 6 for only a few months of the year (53). J.D. Ferguson, referenced in the Brooks AGARDograph (14), has compiled a list of 38 helicopters working in the offshore oil industry that ditched in the North Sea between 1969 and 1996. 150 of the 431 crew and passengers involved died; a survival rate of 65%.

In their 1984 Helicopter Airworthiness Panel (HARP) report into helicopter airworthiness (23), the Civil Aviation Authority (CAA) concluded that the accident rate for helicopters operating over the North Sea was 2.0 per 100,000 flying hours, compared to 0.4 for fixed wing aircraft. A subsequent review of accident data by the CAA in 1995 reported that between 1976 and 1993, the offshore industry had undertaken 2.2 million helicopter operating hours in the transportation of 38 million passengers, for the loss of 85 lives in eight fatal accidents. This represents a fatality rate of 3.86 per 100,000 flying hours (24).

In 1993, Chen et al (22) examined 77 rotorcraft ditchings for the Federal Aviation Authority. 42 helicopters overturned immediately, 9 overturned within 90 seconds, and the condition of the remainder was unknown. In those that overturned immediately, there were 23 fatal, 20 serious and 32 minor injuries. This contrasts with the one fatal, three serious, and three minor injuries seen in those helicopters in which the overturn was delayed. A good example of what happens during an immediate inversion following ditching was provided in 1995 by the testimony of a pilot of Canadian Air Forces' brand-new Bell 412 helicopter off the coast of Labrador.

"I could feel the aircraft hit the water. It immediately turned over to the left, to my side. It felt like it started to fill with water about three-quarters of the way over. I felt a lot of stuff hit me as we rolled over. Once we were upside down, I waited for the thing to fill up with water. I reached for the door handles. I could not find the jettison handles or the main handles. I tried that for a little bit and then gave up trying to find the handles. I grabbed hold of the seat and pulled myself down, popped my belt and now that I had myself held down against the seat, I looked for the handles again. I got hold of the emergency jettison handle and reached on that and gave the door a hit with my shoulder and it didn't go. I hit it a couple of more times with my shoulder and it didn't go. By that time I was starting to panic so I got myself up out of the seat turned myself a little and hit the door with both feet as hard as I could and it finally went. Once I felt the door go, I got myself sorted, turned around and out I went. I didn't know which way was up when I got out so I initially let myself go to feel which direction I was going. I ran into what I believe was a door on the way up, it hit me in the head. Shortly after that I broke the surface. Initially I was pretty panicky because I could not see anything, it was 100% pitch-black."

Clifford (25) conducted a review of U.K. military and world wide civilian helicopter water impacts between 1971-1992. The Civil Aviation Authority published these data in 1996. Of the 61 military helicopters examined, 9 floated after impact, 15 had a delayed inversion and 35 sank immediately. The condition of two helicopters was unknown. The overall survival rate was 83.1%. The summary of occupant injuries from this report is presented in Table 1.

Clifford then reported on world civilian helicopter water impacts (REF). There were 98 accidents but his data are confusing because he changed his terminology. He describes 13 helicopters that sank, 15 that sank after a delay, 37 that sank immediately and 29 helicopters in unknown circumstances. The overall survival rate was 62.5%. These data are presented in Table 2.

61 Water impacts included in analysis
(1971-1992)
273 Occupants involved
13 Fatal accidents - 46 Fatalities
38 Drowned
8 Impact injuries
- 2 from blade strike
- 2 seat failures
- 3 catastrophic impact

Survival rate of 83.1%

18 Accidents involved fatal or serious injuries
7 Accidents accounted for 20 serious injuries:
- 12 spinal compression fractures
- 6 unknown injuries

21.3% of water impacts analysed resulted in fatalities
82.6% of fatalities were the result of drowning (where cause of death was known)
29.5% of water impacts analysed resulted in serious or fatal injuries
60.0% of serious injuries were spinal compression fractures

Table 1 - UK Military Helicopter Water Impacts: Summary of Occupant Injuries. Courtesy Clifford (1996)

98 water impacts included in analysis
(1971-1992)
902 Occupants involved
48 Fatal accidents
- 338 fatalities
- 57 crew members
- 281 passengers

Survival rate of 62.5%
In 24 accidents where the cause of death was known.

- 162 fatalities
- 92 drowned

52 Accidents involved fatal or serious injuries
22 Accidents accounted for 46 serious injuries:
- 14 crew members
- 32 passengers

48.9% of water impacts analysed resulted in fatalities
56.7% of fatalities were the result of drowning (where cause of death was known)
53.0% of water impacts analysed resulted in serious or fatal injuries
Out of 52 accidents that involved serious or fatal injury, 12 (23.0%) resulted in substantial damage to or failure of seats.

Table 2 - World Civil Helicopter Water Impacts: Summary of Occupant Injuries. Courtesy Clifford (1996)

The principal conclusion from all the work was that in approximately 60% of cases the helicopter inverts and sinks immediately, irrespective of whether it is a military or civilian type, and the principal cause of death is drowning. This is in accord with previous data.

The latest review of helicopter ditching accidents, both military and civilian, was conducted at DERA by Turner et al (70) in 1997. Of particular note is the recording of U.S. Army helicopter ditchings in the period between 1972 and 1995. During that time, there were 27 survivable accidents over water, in 9 of them there were fatalities. Unfortunately, only a brief review is made of these 9 accidents, and there is no further mention of the remainder. One unsupported conclusion made in the review states "it is unlikely that the use of passenger emergency breathing devices alone would have reduced the number of fatalities." Yet, a previous statement in 1995 by Benham et al (8) from the same laboratory further supported the development and introduction of emergency breathing systems into service.

On the basis of an extensive review of the worldwide military and civilian helicopter ditching statistics, it is concluded that a significant loss of life can be expected following "survivable" helicopter ditchings (where "survivable" is defined as an accident in which one would expect passengers and crew to survive impact with the water). It is not possible, on the basis of the available evidence, to conclude that the problem is diminishing. For instance, in December 1999, six marines and one sailor were lost when a CH-46 helicopter crashed into the Pacific Ocean, 24 kms. West of Point Loma, California after take off from the U.S.S. Bonhomme Richard.

1.2 The Causes of the Problem

The question of why so many individuals should perish during a survivable accident has been reviewed extensively by Brooks in his AGARDograph on the human factors of escape and survival from helicopters ditching in water. This was updated in a presentation to AGARD in 1997 (17). In any underwater escape, survival will be determined by whether the time required to make an escape can be achieved within an individual's breath-hold time.

1.2.1 Factors determining the time required to make an escape

The key factors, in roughly chronological order, that influence the time it takes to make a successful egress include:

1. Aircrew and passenger anxiety. There is the loud explosion when the engine nozzles, which run at 600°C, are suddenly cooled as they hit the water. This can terrify the pilots and crew and result in "paralyzing anxiety".

2. Equally terrifying, is the sudden in-rushing water. One pilot described this like being hit in the chest by a fire hose.

3. In the process of hitting the water, in at least 50 percent of cases, the helicopter will rapidly sink and rotate. At a time of panic, disorientation and in-rushing water it is necessary to take a good breath before the submersion. Two factors make this difficult: (a) There is often very little warning of the ditching. (b) If the accident occurs in cold water (i.e., water below 15°C) it may be very difficult to control breathing (see below).

4. Disorientation. Broadsmith (11) has modeled various helicopters and concluded that a helicopter may rotate several times before settling on the bottom or stabilizing out. The survivor, under such circumstances, will be disoriented due to false cues signaled by the organs of balance in the inner ear, loss of gravitational references and darkness or, paradoxically, by bright surface sunlight reflecting off the bubbles in the in-rushing water.

5. The victim must release him or herself from the seat harness and, by a process of swimming and dragging, move to, and make an escape through, a door, window, or hatch. This is more difficult for those seated at some distance from an exit. An exit may no longer resemble, in terms of either shape or function, its pre-accident condition. The escape is also made more difficult by: the restrictions of a highly buoyant survival suit; panicking survivors; corpses; personal equipment that has been hurled around the cabin; and seats and consoles displaced during the impact. Finally, the helicopter is primarily designed for emergency egress on land rather than underwater.

6. The victim, possibly injured, certainly terrified, disoriented, and at the limit of breath-holding, is capable of only a few simple actions to save his or her life. At this stage, a poorly designed, complex and tortuous escape route, or a confusing jettison mechanism will easily defeat them.

7. Adding to the problems, Allen et al (2) have demonstrated that underwater, even in the best conditions, humans cannot see further than 3.1 meters.

8. Because the majority of life rafts are stowed inboard, in all this confusion, the survivor has to decide whether to use up precious air by holding his/her breath to locate, release and jettison the liferaft, or make as rapid escape as possible without it (20).

9. Once at an escape exit the jettison mechanism must be found and operated. Brooks and Bohemier (15, 18) observed great difficulty locating, finding and operating escape mechanisms underwater under the best of conditions. The choices open to a potentially disoriented victim vary greatly in terms of: lever position; direction of operation; whether the lever matched the task; and whether the door, window, or hatch jettisoned in or out. Brooks and Bohemier examined 35 types of marine helicopter and noted 23 different types of jettison mechanisms. They concluded that little thought had been put into the design of the helicopter for underwater escape; manufacturers had simply taken the principle of emergency ground egress from their land-based design and adapted it for the marine helicopter.

10. Even if the survivor has made a safe exit from the fuselage, it is still necessary to breath-hold until reaching the surface. As the helicopter sinks, it is not uncommon to have to make an escape in 5-10 metres of water. Due to Boyle's Law, below about 5 metres, neither the buoyancy in the survival suit or the lifejacket will bring the person safely to the surface. It is therefore necessary to swim. This requires hard work and significantly shortens breath-hold time.

1.2.2 Factors determining the time available to make an escape

In the absence of any artificial aid, the time available to make an escape from a ditched, submerged helicopter is determined by maximal breath-hold time. Unfortunately, sudden immersion in cold water produces a series of physiological responses, one of which is an increase in respiratory drive and the loss of the ability to breath-hold. In 1989, Tipton (62) described the initial responses to immersion in cold water which have been given the generic title "cold shock (60); they begin in water at about 25°C and peak in water at 10°C (68). They include: an inspiratory "gasp" response and uncontrollable hyperventilation producing a significant reduction in breath-hold time and an increase in blood pressure, heart rate and the consequent work required of the heart. Tipton et al demonstrated that cardiac arrhythmias are not uncommon during the first minute of immersion; they are particularly prevalent if the face is immersed immediately following a breath-hold (67).

The cardiovascular responses initiated by immersion can be particularly hazardous for those with pre-existing cardiovascular disease. For the otherwise fit and healthy individuals it is the respiratory responses that represent the greatest threat. Indeed, a good deal of statistical, anecdotal and experimental evidence exists to support the view that it is the loss of control of respiration during the first minute of immersion, rather than hypothermia, which represents the greatest threat associated with immersion in cold water (60). This threat is increased if the immersion is in choppy water where the airways will be repeatedly challenged, or involves a period of forced submersion, such as in a sinking craft.

Reduced maximum breath-hold times resulting from the gasp response have been reported by several authors (35, 36, 39, 57, 61). Hayward et al (35) reported that over a water temperature range of 0-15°C, the maximum breath-hold time of subjects was reduced to 25-30% of that seen before submersion, and to 30-60% of that seen on immersion in thermoneutral water. In some individuals, maximum breath-holds of 1-2 minutes in air can be reduced to a matter of seconds on immersion in cold water. As the cold shock response demonstrates both spatial and temporal summation, the size of the reduction in breath-hold time is dependent on the surface area of skin exposed to the cold stimulus and the rate of change of skin temperature. One consequence of this is that clothing can reduce the cold shock response to some extent. Tipton and Vincent (61) reported that the mean maximum breath-hold time of 18 subjects in air was 45 seconds. When performing an underwater escape from a mock-up of a Bell 212 submerged in water at 5°C the corresponding time was 9.5s when wearing cotton overalls; 12.2s when wearing cotton overall plus a "shorty" wet suit; and 19.2 seconds when wearing cotton overalls plus an uninsulated helicopter passenger "dry" suit.

In 1995, Tipton and his colleagues (68) reported that the average maximum breath-hold time of subjects performing a simulated helicopter underwater escape in water at 10°C whilst wearing heavy underclothing and a helicopter passenger "dry" immersion suit, was 17.2 seconds. The corresponding time for subjects wearing the Royal Navy winter sea helicopter aircrew equipment assembly and an aircrew helmet was 21 seconds in water at 5 and 15°C (69).

1.3 The Solution? Rationale for the provision of Emergency Breathing Systems

Despite the evidence to suggest that the cold shock response represents the greatest hazard to be faced on immersion in cold water, the preoccupation remains with hypothermia. This is reflected in: search and rescue policies; the standards, guidelines and specification for immersion protective clothing – few, if any of which, include consideration of the protection provided against cold shock; and the claims made for immersion protective equipment. Whilst it is now almost unthinkable that anyone should fly over cold water in a helicopter without protection against hypothermia in the form of an immersion suit, many still fly without any respiratory protection. Until relatively recently EBS were not even considered for aircrew, let alone passengers.

It is impossible to accurately predict the time required to make a successful underwater escape from a ditched inverted helicopter. Estimations from groups such as the Coast Guard, military and civilian operators in the North Sea and training establishments suggest that in reasonable conditions (lighting, number of passenger, seating position in cabin) 40-60 seconds are required (68).

Brooks and Muir (19) have recently completed a study to measure the escape times for a full complement of passengers in the Super Puma helicopter. In the first part of the study, fit, healthy helicopter underwater escape trainer (HUET) Instructors and Canadian Navy divers represented the 18 passengers. The HUET (Modular Egress Training Simulator [METS™]) was in an Offshore Petroleum Industry Training Organization (OPITO) standard, 18 exit, configuration. The subjects conducted a total of four underwater escapes; one of these was in the dark. Breath-holding times were measured from the time the heads of the subjects were submerged to the time when the head of the first and the last subjects to egress broke the surface of the water. It took 17 seconds from the HUET hitting the water to the heads being submerged.

In the first submersion and inversion, the first subject took 43.5 seconds to escape and the last subject 109.2 seconds, representing a breath-hold requirement of 27-92 seconds. Ten out of 18 subjects used the emergency air supply in this immersion. In subsequent runs the breath-holding time of the last person out ranged from 33–38 seconds. The EBS provided was used by; four, six, and seven subjects in the subsequent three tests.

In the second part of the study, 15 fit, healthy HUET Instructors and Canadian Navy divers repeated the same experiment in the METS™ in the Canadian Super Puma Hibernia oil field offshore helicopter configuration. The breath-holding time of the last person out ranged from 28-52 seconds in daylight, and from 38-55 seconds in darkness. The EBS was used by five subjects in the first immersion, six subjects in the second immersion, and eight subjects in each of the last two immersions. These were the best times that the highly qualified instructors could achieve in warm water when fully prepared and practiced.

It is the short fall between the maximum breath-hold time of well-protected individuals performing simple mock helicopter underwater escapes in cold water (about 17-21 seconds), and the time thought necessary to make an escape in a real accident (40-60 seconds), which provides the rationale for the provision of some form of EBS. Some have argued that in a real accident individuals would hold their breath longer than the time measured in the laboratory during a mock up. This position ignores firstly, the fact that the reduction in breath-hold time is caused by uncontrollable cold shock, not conscious decision and secondly, that in a real accident it is very possible that the conditions to which victims will be exposed will be much worse than those employed in the laboratory.

In 2000, Brooks et al (21) provided further evidence for the requirement for an additional breathing aid. They measured the breath-holding ability in water of 228 students who either worked in the offshore oil industry or were training for potential positions offshore. The group was randomly selected from the Survival Systems Ltd. helicopter underwater escape training classes between January and March 2000. The average (standard deviation) breath-holding